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INDICATOR OF REMAINING ENERGY IN STORAGE CELL OF IMPLANTABLE MEDICAL DEVICE

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TECHNICAL FIELD

This document relates generally to energy storage cells and particularly, but not by way of limitation, to an indicator of remaining capacity of an energy storage cell, such as in an implantable pacer/defibrillator device.

BACKGROUND

Implantable medical devices include, among other things, cardiac rhythm management (CRM) devices such as pacers, cardioverters, defibrillators, cardiac resynchronization therapy (CRT) devices, as well as combination devices that provide more than one of these therapy modalities to a subject. Such devices are typically powered by self-contained energy sources, such as batteries. It is useful to know how much energy capacity remains in a battery carried within an implanted medical device, such as to ascertain when the implanted device should be explanted from the subject and replaced by a device with a fresh battery. Determining how much energy is left in a battery is particularly difficult when a measured battery characteristic (e.g., the quiescent voltage at the battery terminals) does not change appreciably during a large portion of the battery life. Yet such a characteristic is particularly desirable for use in a cardiac rhythm management device because it provides a predictable battery characteristic during that large portion of the battery life.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, which are not necessarily drawn to scale, like numerals describe substantially similar components throughout the several views. Like numerals having different letter suffixes represent different instances of substantially similar components. The drawings illustrate generally, by way of

example, but not by way of limitation, various embodiments discussed in the present document.

FIG. **1** is a schematic diagram illustrating generally, by way of example, but not by way of limitation, one example of a system, including an implantable device and a remote interface.

FIG. **2** is a flow chart illustrating generally, by way of example, but not by way of limitation, one example of a method of determining remaining battery capacity.

FIG. **3** is a current vs. time graph illustrating generally one example of a substantially constant current pulse drawn from the battery.

FIG. **4** is a corresponding voltage vs. time graph illustrating generally one example of a battery terminal voltage signal during the substantially constant current pulse of FIG. **3**.

FIG. **5** is a voltage vs. time graph, similar to FIG. **4**, but illustrating a conceptual example for which the battery is near the middle of its useful life.

FIG. **6** is a conceptualized voltage vs. time graph of quiescent battery terminal voltage vs. depth of discharge of a MnO_2 battery.

FIG. **7** is a conceptualized graph of a polarization angle (i.e., $90 - \theta$), representing the slope of the battery terminal voltage during the constant current pulse of FIG. **3** vs. depth of discharge of a MnO_2 battery.

FIG. **8** is a flow chart illustrating generally one example of a technique that uses both polarization angle (or the slope, or similar indication using the difference between the two battery terminal voltage measurements obtained during the constant current pulse) and quiescent battery terminal voltage (obtained at a time other than during the constant current pulse) for determining the remaining energy in a MnO_2 battery.

FIG. **9** is a flow chart illustrating generally a technique that splits the curve of FIG. **7** into a beginning of life segment that precedes the minima, and an end of life portion that succeeds the minima, and that uses remaining energy to switch between the two segments.

FIG. **10** is a flow chart illustrating generally another technique that splits the curve of FIG. **7** into a beginning of life segment that precedes the minima, and an end of life portion that succeeds the minima, and that uses a determination of quiescent battery voltage to switch between the two segments.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments, which are also referred to herein as "examples," are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that the embodiments may be combined, or that other embodiments may be utilized and that structural, logical and electrical changes may be made without departing from the scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims and their equivalents.

In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one. In this document, the term "or" is used to refer to a nonexclusive or, unless otherwise indicated. Furthermore, all publications, patents, and patent documents referred to in this document are incorporated by reference herein in their entirety, as though individually incorporated by reference. In the event of inconsistent usages between this documents and those documents so incorporated by reference, the usage in the incorporated reference(s) should be considered supplementary to that of this document; for irreconcilable inconsistencies, the usage in this document controls.

FIG. **1** is a schematic diagram illustrating generally, by way of example, but not by way of limitation, one example of a system **100**. In this example, the system **100** includes an implantable device **102** and an external remote interface circuit **104**. In the illustrated example, the implantable device **102** represents a cardiac rhythm management (CRM) device, and the external remote interface circuit **104** represents

a remote programmer device. The device **102** includes an energy storage cell, such as a battery **106**. The battery **106** provides energy to load circuits **108**. For an implantable CRM device, such load circuits **108** typically include, among other things, analog circuits, a digital microprocessor circuit, a memory circuit, pacing therapy circuits, and defibrillation therapy circuits. The load circuits **108** typically draw a relatively stable quiescent current from the battery **106**. One exception, however, is a charging circuit for occasionally charging one or more defibrillation energy storage capacitors to a high voltage. This stored high voltage is used for subsequently delivering a defibrillation shock to a subject. During such occasional operation, the high voltage charging circuit typically adds a substantial additional load current beyond the background quiescent current drawn by the load circuits **108**.

Because the battery **106** typically has a finite energy storage capacity, there is a need to obtain an indication of how much stored energy remains in the battery **106**. This battery status information is useful to a physician or other caregiver, such as for determining when the battery **106** is depleted enough to require replacing the battery **106** (or, more typically, replacing the entire implantable device **102**). This battery status information is also useful for other components of the implantable device **102**. For example, near the end of the useful life of the battery **106**, it may be desirable to automatically turn off one or more "nonessential" circuits to conserve energy. This preserves and prolongs the ability of other more "critical" circuits to provide therapy to the subject.

In certain circumstances, the terminal voltage (across the battery terminals **110A-B**) during quiescent current draw does not vary appreciably over a significant portion of the useful life of the battery **106**. This is true, for example, during a significant portion of the beginning of the useful life of the battery 106, where the battery **106** includes a manganese dioxide (MnO_2) battery chemistry.

The system **100** provides, among other things, devices and methods for determining the battery status, that is, the remaining energy in the battery **106**. This includes a pulsed constant current source/sink circuit **112**, which is connected across

the battery terminals **110A-B**. A voltage detector circuit is also connected across the battery terminals **110A-B**, such as for measuring a battery terminal voltage one or more times during a constant current pulse drawn from the battery **106** by the current source/sink circuit **112**. The voltage detector circuit **114** includes at least one output coupled, at node/bus **116**, to at least one input of an analog-to-digital (A/D) converter circuit **118**. The voltage detector circuit **114** outputs a voltage measurement of the battery terminal voltage. The A/D converter circuit **118** receives and digitizes this voltage measurement. At least one output of the A/D converter circuit **118** is coupled, at node/bus **120** to at least one input of a microprocessor, controller, or other processor circuit **122**. The processor **122** includes stored executable instructions **124**, such as for performing various operations and issuing control signals to other circuits of the implantable device **102**.

The processor **122** includes a difference circuit **126**, which includes at least one input that is coupled, at the node/bus **120**, to the at least one output of the A/D converter circuit **118** to receive the digitized battery terminal voltage measurements. The difference circuit **126** calculates a difference between first and second voltage measurements taken (separated by a known time interval, Δt) during the constant current pulse drawn from the battery **106** by the current source/sink circuit **112**. In one example, this difference is expressed as a "polarization angle," as discussed below. In another example, this difference is expressed as a "slope" or "rate of change," as discussed below. The processor **122** includes an onboard or separate memory **128**. The memory **128** includes stored data **130**. The stored data **130** is representative of remaining battery energy as a function of the difference between the first and second voltage measurements taken during the constant current pulse drawn from the battery **106** (or, alternatively, as a function of the "polarization angle," the "slope," or "rate of change"). As discussed below, the processor **122** executes instructions that use the difference to look up the remaining battery energy. The memory **128** includes at least one storage location **132** for storing an indicator of the remaining battery energy. In one example, the implantable device **102** further

includes a telemetry or other communication transceiver circuit **134**. The transceiver **134** includes at least one input that is coupled to at least one output of the processor **122**, such as at a communications node/bus **136**. The transceiver **134** transmits information indicative of the remaining energy indicator in the storage location **132** to the external remote interface circuit **104**. Among other things, this informs the physician or other caregiver of how much useful life remains in the battery **106** before replacement of the battery **106** (or the device **102**) is needed.

FIG. **1** illustrates an example in which the battery status determination is made within the implantable device **102**, with the result communicated to the external remote interface circuit **104**. In an alternate example, however, the processor includes instructions to control the obtaining of the first and second voltage measurements, and these first and second voltage measurements (or, alternatively, the difference between these first and second voltage measurements) are communicated by the transceiver **134** to the external remote interface circuit **104**. In this example, the external remote interface circuit **104** includes instructions for performing the necessary computations for determining battery status.

FIG. **2** is a flow chart illustrating generally, by way of example, but not by way of limitation, one example of a method of determining remaining battery capacity, such as for a MnO_2 battery for which the battery terminal voltage does not vary appreciably during quiescent current conditions—particularly during the beginning portion of the useful life of the battery **106**. In the example of FIG. **2**, at **200**, the constant current source/sink **112** is turned on to draw a substantially constant current having an amplitude (in addition to the quiescent/background current drawn by the load circuits **108**) of approximately between 2 amperes and 4 amperes, such as about 3 amperes. In one example, this constant current pulse is of a fixed predetermined duration that is approximately between 3 seconds and 30 seconds, such as about 6 seconds. At **202**, first and second voltage measurements (separated by the known time interval, Δt) are obtained, such as by the voltage detector circuit **114**, during the constant current pulse. In one example, the first voltage measurement is obtained just after the constant current pulse commences

(e.g., after any initial turn-on transients stabilize), and the second voltage measurement is obtained just before the constant current pulse ceases. At **204**, an indication of the difference between the first and second voltage measurements is computed, such as by the difference circuit **126**. This indication of the difference may, but need not, be expressed as a slope or rate of change of the battery terminal voltage during the constant current pulse, or as a "polarization angle," as discussed below. At **206**, the indication of the difference is used to compute the remaining energy of the battery **106**. At **208**, an indication of the remaining energy of the battery **106** is stored in the memory location **132**. At **210**, information indicative of the remaining energy of the battery **106** is communicated from the implantable device **102**, such as from the transceiver **134** to the external remote interface circuit **104**, to be displayed to a physician or other caregiver.

FIG. **3** is a current vs. time graph illustrating generally one example of a substantially constant current pulse drawn from the battery **106**, such as by the current source/sink circuit **112**. The current pulse is turned on at time t_1, and reaches its full amplitude I_o by time t_2. This current amplitude I_o is in addition to any quiescent/background current being drawn from the battery **106**, such as by the load circuits **108**. The amplitude remains stable at I_o at time t_3, just before the current pulse is turned off at t_4. The amplitude returns to zero at time t_5.

FIG. **4** is a corresponding voltage vs. time graph illustrating generally one example of a battery terminal voltage signal during the substantially constant current pulse of FIG. **3**. Initially, the battery terminal voltage is at a background or quiescent voltage V_Q. At time t_1, when the current pulse is turned on, the battery terminal voltage begins to drop until it reaches the first loaded voltage V_{1B} at time t_2. During the substantially constant current pulse, the battery terminal voltage continues to drop slightly until it reaches the second loaded voltage V_{2B} at the time t_4. At that time, the substantially constant current pulse is turned off, and the battery terminal voltage returns to the quiescent voltage V_Q at time t_5. FIG. **4** illustrates a conceptual example for which the battery **106** is near the beginning of its useful life.

FIG. **5** is a voltage vs. time graph, similar to FIG. **4**, but illustrating a conceptual example for which the battery **106** is near the middle of its useful life. Comparing FIGS. **4** – **5**, the battery terminal voltage drops, between times t_2 and t_4, more quickly when the battery **106** is near the beginning of its useful life (see FIG. **4**) than when the battery **106** is near the middle of its useful life (see FIG. **5**). This rate of change, or "slope," therefore, provides a useful indicator of the energy remaining in the battery **106**. The slope can alternatively be expressed as a polarization angle θ, as illustrated in FIGS. **4** – **5**. The polarization angle $\theta = \tan^{-1}(\Delta t/\Delta v)$, where Δt is a time difference and Δv is a corresponding voltage difference. FIGS. **4** – **5** illustrate θ_1 (for the beginning of the useful life of the battery **106**) as being less than θ_2 (for the middle of the useful life of the battery **106**.

FIG. **6** is a conceptualized voltage vs. time graph of quiescent battery terminal voltage vs. depth of discharge of a MnO_2 battery **106**. As seen in FIG. **6**, the quiescent battery terminal voltage does not vary appreciably during a beginning portion of the MnO_2 battery life, when the battery is relatively full of stored energy. This makes quiescent battery terminal voltage difficult to use for determining the battery's stored energy status during the beginning portion of the MnO_2 battery's useful life.

FIG. **7** is a conceptualized graph of a polarization angle (i.e., $90 - \theta$), representing the slope of the battery terminal voltage during the constant current pulse, such as between times t_2 and t_3 or between times t_2 and t_4. As seen in FIG. **7**, the polarization angle changes significantly during the beginning portion of the MnO_2 battery life, when the battery is relatively full of stored energy. This makes such slope or polarization angle a useful indicator for determining the battery's stored energy status, particularly during the beginning portion of the MnO_2 battery's useful life. By measuring the battery terminal voltage at two times during the constant current pulse, taking the difference between these measurements, and dividing by the time difference, Δt, between these two battery terminal voltage measurements, the angle θ is obtained. The polarization angle quantity $(90 - \theta)$, where θ is expressed in degrees, is compared to a lookup table or equation fit (from

data previously obtained from similar batteries) of remaining battery energy vs. (90 – θ). This permits the remaining battery energy to be determined.

However, as seen in FIG. **7**, the "bathtub" shaped curve of polarization angle vs. depth of discharge maps one value of the polarization angle to two different values of remaining battery energy. The present inventors have recognized several techniques for overcoming this potentially confounding factor. First, the polarization angle can be used to determine remaining battery energy during a beginning portion of the battery's useful life, then switching to use the quiescent battery terminal voltage to determine remaining battery energy during a later portion of the battery life, as discussed below with respect to FIG. **8**. Second, the curve of FIG. **7** can be divided up into a beginning of life segment and an end of life segment, and the polarization angle or remaining energy can be used to switch between the two segments, such as discussed below with respect to FIG. **9**. Third, the curve of FIG. **7** can be divided up into the beginning of life and end of life segments, and a quiescent battery terminal voltage can be used to switch between the two segments, such as discussed below with respect to FIG. **10**.

FIG. **8** is a flow chart illustrating generally one example of a technique that uses both polarization angle (or the slope, or similar indication using the difference between the two battery terminal voltage measurements obtained during the constant current pulse) and quiescent battery terminal voltage (obtained at a time other than during the constant current pulse) for determining the remaining energy in the MnO_2 battery. At **800**, upon implantation of the device **102**, it is the beginning of the battery's useful life. At **802**, the polarization angle (or the slope, or similar indication using the difference between the two battery terminal voltage measurements obtained during the constant current pulse) is used to determine the remaining energy, such as discussed above with respect to FIG. **2**. At 804, the resulting remaining battery energy is compared to a threshold (e.g., corresponding to the minima of the curve of FIG. **7**). If the remaining energy exceeds the threshold, then process flow returns to **802**—remaining battery energy continues to be computed using polarization angle. However, if at **804** the remaining energy is less

than the threshold, then subsequently, battery terminal voltage is measured under quiescent current conditions and used to determine remaining energy, at **806**. This includes comparing the measured quiescent battery terminal voltage to a lookup table of remaining energy vs. quiescent battery terminal voltage. As seen in the curve of FIG. **6**, during this portion of the battery life, quiescent battery terminal voltage changes more appreciably as a function of remaining battery energy. Therefore, quiescent battery terminal voltage provides a more useful indicator of remaining battery indicator during this latter portion of the battery's useful life than during the earlier portion of the battery's useful life, when the curve is relatively flat.

FIG. **9** is a flow chart illustrating generally a technique that splits the curve of FIG. **7** into a beginning of life segment that precedes the minima, and an end of life portion that succeeds the minima, and that uses remaining energy to switch between the two segments. At **900**, when the device **102** is initially implanted, the MnO_2 battery is at the beginning of its useful life. At **902**, the polarization angle (or the slope, or similar indication using the difference between the two battery terminal voltage measurements obtained during the constant current pulse) is used to determine the remaining energy, such as discussed above with respect to FIG. **2**, using the beginning of life segment of the curve of FIG. **7**. At **904**, the resulting remaining battery energy is compared to a threshold (e.g., corresponding to the minima of the curve of FIG. **7**). If the remaining energy exceeds the threshold, then process flow returns to **902**—remaining battery energy continues to be computed using polarization angle and the beginning of life segment of the curve of FIG. **7**. However, if at **904** the remaining energy is less than the threshold, then subsequently, remaining battery energy is subsequently computed at **906** using polarization angle and the end of life segment of the curve of FIG. **7**. At **904**, as an alternative to comparing remaining energy to a threshold, the corresponding polarization angle can be compared to a corresponding threshold (e.g., corresponding to the minima of the bathtub curve of FIG. **7**).

FIG. **10** is a flow chart illustrating generally another technique that splits the curve of FIG. **7** into a beginning of life segment that precedes the minima, and an end of life portion that succeeds the minima, and that uses a determination of quiescent battery voltage to switch between the two segments. At **1000**, when the device **102** is initially implanted, the MnO2 battery is at the beginning of its useful life. At **1002**, the polarization angle (or the slope, or similar indication using the difference between the two battery terminal voltage measurements obtained during the constant current pulse) is obtained for determining the remaining energy, such as discussed above with respect to FIG. **2**. At **1004**, a quiescent battery terminal voltage measurement is obtained. At **1006**, the quiescent battery terminal voltage is compared to a threshold value (e.g., corresponding to the minima of the curve of FIG. **7**). If the threshold quiescent battery terminal voltage measurement is greater than or equal to the threshold value, then the first (beginning of life) segment of the curve of FIG. **7** is used to determine remaining battery energy at **1008**. Otherwise, at **1010**, the second (end of life) segment of the curve of FIG. **7** is used to determine the remaining battery energy.

Although the above examples have been described for an example using an MnO_2 battery chemistry, the present devices and methods will also be useful for determining battery status for batteries of other chemistries such as, for example, a silver vanadium oxide (SVO) battery chemistry. For example, for a SVO battery chemistry, the above-described techniques using polarization angle to determine remaining battery life may require that the SVO battery not be discharged too quickly, thereby diminishing the polarization angle effect from which remaining battery life is determined. Also, although the above-described techniques are particularly useful for batteries where the quiescent battery terminal voltage does not vary appreciably over the usable life of the body, such techniques are not limited to use with such batteries, but can be used with other batteries as well.

It is to be understood that the above description is intended to be illustrative, and not restrictive. For example, the above-described embodiments may be used in combination with each other. Many other embodiments will be apparent to those of

skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.